A Customizable MR Brain Imaging Atlas of Structure and Function for Decision Support.

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Abstract

We present a MR brain atlas for structure and function (diffusion weighted images). The atlas is customizable for contrast and orientation to match the current patient images. In addition, the atlas also provides normative values of MR parameters. The atlas is designed on informatics principles to provide context sensitive decision support at the time of primary image interpretation. Additional support for diagnostic interpretation is provided by a list of expert created most relevant 'Image Finding Descriptors' that will serve as cues to the user. The architecture of the atlas module is integrated into the image workflow of a radiology department to provide support at the time of primary diagnosis.

Introduction

Image atlases are available in both paper and electronic format. Two important MR imaging atlases with structures outlined are available online from the groups at University of Washington [1] and Harvard [2]. The Washington group, as part of the Digital Anatomist Project, has developed atlases from MR and dissection images of normal subjects. The Harvard group has MR based atlases of normals and subjects with pathology. Both atlases are interactive to the extent the user can toggle between contours and annotations as well as use the atlas in a 'Quiz Mode'. While these atlases are effective as a general-purpose teaching tool, decision support at the time of image study interpretation may require a more dynamic atlas. For example, the atlases mentioned above are available at different but fixed orientations (axial, coronal) and contrasts (spin-lattice relaxation (T1), spin-spin relaxation (T2), proton density (PD)). A more effective method for decision support will be an atlas that can match the patient data both in terms of image contrast and image orientation. This is particularly important when several factors can confound establishing correspondences between atlas and patient structures: differences in partial volume effects arising from differences in image resolution of atlas and patient, orientation differences between atlas and patient, and intensity and contrast differences of the atlas and patient arising from different image acquisition conditions. In addition to the notion of customizability, the increasing use of functional imaging such as diffusion-weighted imaging requires a more comprehensive atlas that will extend current MR based anatomical atlases. Another trend in MR imaging is the move toward quantitation that includes T1 and T2 relaxometry, diffusion tensor imaging, and magnetization transfer contrast for more accurate disease characterization. However establishment of quantitative techniques requires a normative atlas that can be used for comparative purposes.

With these requirements as a background, we describe an atlas under construction that enhances the current online atlas efforts of other groups in several ways: (i) the atlas orientation and contrast is customizable to the patient dataset, (ii) extension to atlases of MR functional information: diffusion weighted atlases, (iii) quantitative atlases of T1, T2, diffusion tensor and magnetization transfer contrast and, (iv) integration in an imaging workflow that permits automated customization and availability at a PACS diagnostic workstation.

Methods

Generation of the Atlases and Contrast Customization: The images for the structure and function atlas are from the same subject. The images for the contrast customizable atlas, diffusion and magnetization contrast atlases were generated in three different imaging sessions but were aligned to the diffusion-weighted study to normalize all the atlas images to common frame of reference.

Contrast Customizable Structural Atlas: Images are acquired using multi-echo and saturation recovery MR sequences as described earlier [3,4]. The T1, T2 and proton density maps derived from this dataset can then used to synthesize images acquired with any one of the following imaging sequences (2D or 3D): spin echo, fast spin echo, inversion recovery including Fluid Attenuated Inversion Recovery (FLAIR) and Short Time Inversion Recovery (STIR), gradient echo sequences of different flavors (refocused and spoilt). It is possible to synthesize any sequence that depends on T1, T2 and PD parametric values provided the intensity equation is available for the sequence.

Functional Atlas: Diffusion weighted images are acquired using a special sequence

designed by us [5] and the diffusion tensor (DT) value was calculated at each pixel according to [6]. Two rotationally invariant indices were derived from the DT values: the apparent diffusion coefficient (ADC) and the fractional anisotropy (FA). In addition to the atlas of these indices, maps of diffusion-weighted images can also be synthesized for any value of the applied diffusion gradient (strength and duration). These synthesized maps are of potential use since many clinical interpretations are still performed on diffusion-weighted images rather than on the calculated parametric images.

Quantitative Atlas: This feature provides support for quantitative imaging and can potentially be used as a normative database to compare with values obtained in the patient study. Each labeled structure in the atlas will have quantitative values of the following parameters: T1, T2, PD, ADC and FA. These values are the average of all the pixels in the selected structure and are pre-computed and stored for each structure along with the location of the contours. Additionally, a user can also draw a region of interest and parametric value averages for the region will be calculated interactively using direct pixel values from the parametric maps.

Atlas Orientation Customization: A 3D voxel intensity based algorithm is applied to obtain the global affine transformation required to align the patient and reference datasets. This algorithm uses a cost function defined by the mean of the square of the differences of corresponding voxel intensities in the reference and target volumes to search the transformation space for the parameters that minimize this function [7,8]. A multi-variate Marquardt-Levenburg minimization is used to search for the spatial transformation that registers the two image datasets. This algorithm is clearly dependant on the signal intensity match of equivalent pixels in the target and reference sets and the contrast customizable atlas is an effective method to provide a contrast/intensity matched reference atlas for a wide range of patient data. The transformation from this registration is used to reformat the contrast-customized atlas to match patient image orientation.

Atlas Annotation: An expert contours structures on the atlas and the labeling follows the hierarchy in NeuroNames [9]. The hierarchy in NeuroNames is at a level of detail that is not visualized on MR images. However, we provide the sub-structure list to all contoured structures since this list may aid the radiologist in the interpretation process. In addition to annotated structures, the neuroradiologists in our group (SES, GD) have developed a list of 'Image Finding Descriptors' that provides for each brain region, a comprehensive list of attributes to describe the abnormalities specific to the region. Users can access this list for any of the contoured structures in the atlas.

Integration in the radiology workflow: Currently, the atlas is implemented as a standalone system. However, in order to provide decision support at the time of diagnostic interpretation, the atlas will be integrated in an imaging workflow: (i) Images from the acquisition devices are transmitted to Picture Archiving and Communications System (PACS) in Digital Imaging and Communications in Medicine (DICOM) format. (ii) Arrival of a brain imaging study in the PACS archives automatically triggers the atlas customization algorithms. (iii) Atlas customization requires information about the current imaging study. This is extracted from the DICOM image header and includes for each image series of the study: imaging sequence type, image sequence settings (such as echo time (TE)/ repetition time (TR)/ inversion time (TI), Flip Angle (θ)), voxel resolution, volume coverage, image orientation. (iv) Contrast and orientation customization are performed on the atlas using this information of the current patient image series. The atlas is registered to the image series that has the maximum volume coverage. (v) The transformation matrix from this registration is used to generate transformation matrices for other image series of the study since spatial location/orientation with respect to a common reference (magnet coordinate system) is specified for each image series. The transformation matrices are then transferred to the diagnostic workstation and the atlas is reformatted at the workstation in real-time. Two points in this architecture should be noted: (i) registration, which could take 20 to 30 minutes is performed off-line and only reformatting which is relatively fast, is performed at the diagnostic workstation. (ii) Further, customized atlases are not transferred between the off-line and diagnostic workstation but only the transformation matrices, which are very small text files.

Results

Figure 1 is a panel showing the functional atlas: here different indices calculated from the diffusion tensor values are shown to visualize diffusion. The user can select between viewing the eigenvalues of diffusion coefficient (top row), color maps of the fiber orientation or anisotropy (lower left and center) or fractional anisotropy (lower right). Figure 2 is a screenshot showing the atlas customized to the current patient study (left top panel). For comparison, the atlas prior to registration to patient image is shown in the right panel. The match between atlas and patient orientation is clearly evident after the registration and reformatting. The

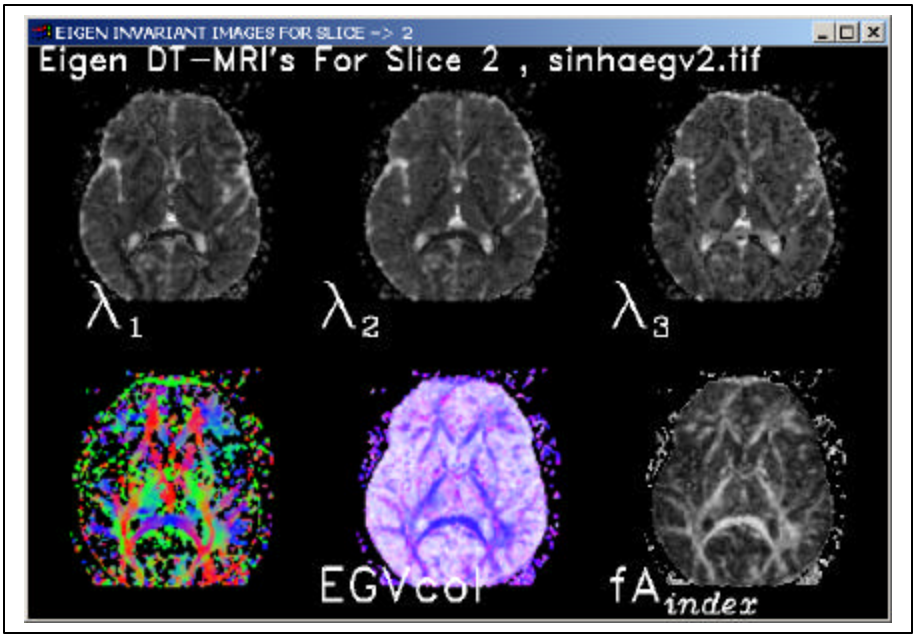

Figure 1: The diffusion weighted atlas can be displayed to highlight different information: (i) eigenvalues of the diffusion tensor (top row), (ii)color map of the fiber directions (bottom right,left), (iii) color map of diffusion anisotropy , and (iv) as the fractional anisotropy.

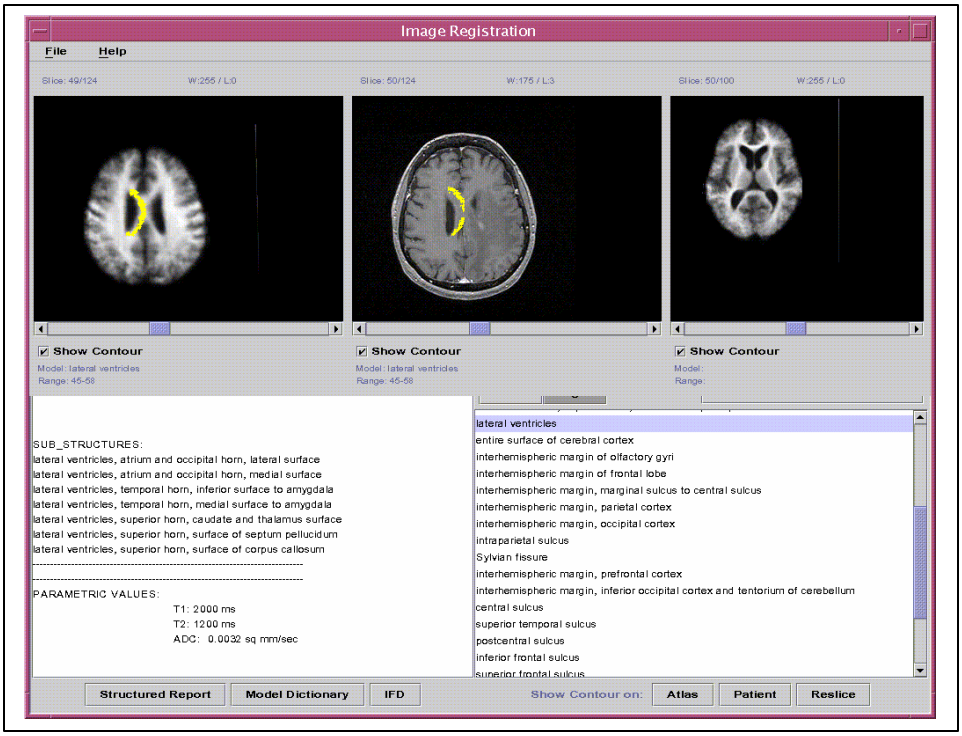

Figure 2: The atlas customized to the contrast and orientation of the patient (center image of top panel) is shown on the left. The original atlas before customization is shown on the right at the same image number. The level of the customized atlas is matched to that of the patient but local differences still exist since only a global alignment is performed. A structure (lateral ventricles highlighted) can be selected from the list (right, lower panel) and will be displayed on the customized atlas. Alternatively all structures at each level can be shown outlined. The substructures belonging to the selected structure are shown on the left panel as well as the average values of MR relaxometric and diffusion data for the selected structure.

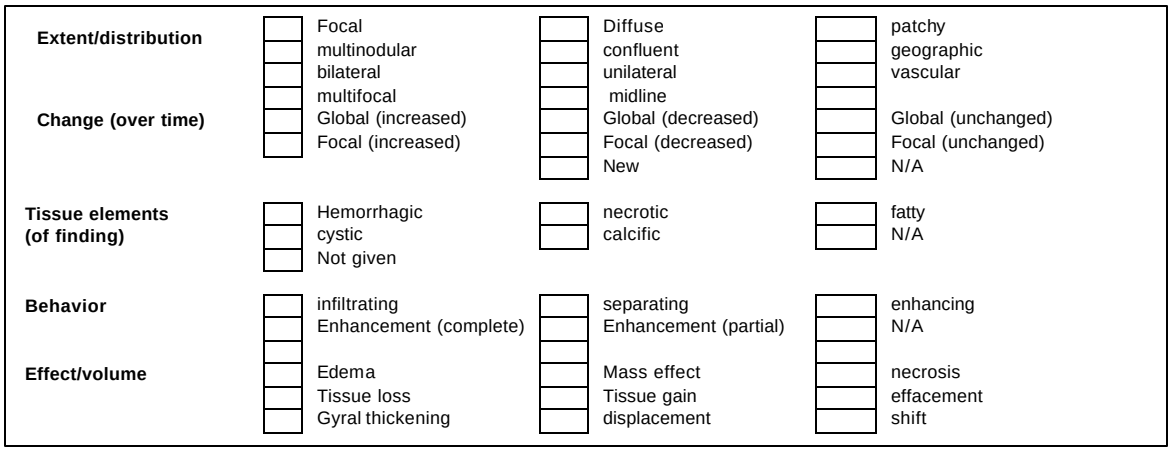

Figure 3: A portion of the 'Image Finding Descriptors (IFD)' list for abnormalities of white or gray matter tissue. The list appropriate to a structure is displayed from the Atlas module (Figure 2, Button 'IFD'). This cues the user to look for abnormality attributes listed in the 'IFD' while examining any region (structure) in the current patient study.

list of atlas structures for which contours are available is shown in the lower right panel. The substructure(s) for a selected structure are shown in the top half of the lower left panel, and the quantitative values of MR parameters are shown for the selected structure below. Figure 3 is a part of a list of 'Image Finding Descriptors (IFD)' used to describe diseases of the Gray/White Matter.

Discussion

This is the first attempt at providing a customizable MR brain atlas of structure and function for decision support at the time of diagnostic interpretation. In addition to customizing the atlas to match the patient, it can also be used in a 'Teach Mode' where the user can interactively generate contrast for a range of MR pulse sequences. However, it should be kept in mind that the synthesized images are not capable of accurately modeling flow and susceptibility effects in gradient echo based images and thus will not entirely match patient images acquired from gradient echo sequences in regions of flow and/or field inhomogeneities.

Availability of quantitative parametric values will certainly extend the clinical use of the atlas. Currently, it is true that quantitative relaxometry in not routinely used clinically but it is rapidly being established as a research tool. A number of recent reports have underlined the utility of quantitative T1 and T2 values to more accurately characterize disease [10, 11]. Further, recent advances in fast scanning methods to obtain T1 and T2 values in clinically relevant times will certainly see increased usage of quantitative values in routine clinical applications [12]. On the other hand, diffusion imaging from the outset, has been a quantitative method and normative data for ADC and FA values will be a useful decision support tool in evaluating various brain disease states. An atlas with normative quantitative data as proposed here will provide baseline values for comparison to patient data.

The registration algorithm used here is a global transformation and does not model the local deformations arising from physiological and pathological variations. This level of global alignment suffices since our goal is to provide an atlas view that is only approximately at the level, orientation and contrast of the patient images. Future work in this area will however integrate a local deformation algorithm for more accurate mapping to the patient data. Future work will also include other modifications to the registration algorithm to accommodate a wide range of clinical data including truncated volumes, poor voxel resolutions, and large spatial displacements.

The atlas also provides a list of 'Image Finding Descriptors'; this feature is added in order to provide users with an expert created list of possible abnormalities and most relevant attributes that describe the abnormality. This will enable the user to look for the attributes listed for any structure/tissue type in the current patient images. Future work will enable users to automatically link the terms in the 'Image Finding Descriptors' list to an on-line literature search engine (e.g., Medline).

The technical aspects of the decision support atlas are in place and it will be evaluated first in a standalone mode and then in a clinical setting integrated in a PAC system. Clinical studies with control groups will evaluate whether the usage of this atlas improves the speed and/or accuracy (diagnosis or structure identification) of assessing new cases as well as the impact on novices and experts. As far as we are aware this is the first report of a contrast and orientation customizable atlas of structure and function. It should provide additional benefits to the user over currently available on-line atlases. Other advantages of this system are the availability of quantitative MR parametric values, the functional atlas as well as support for diagnostic interpretation in the form of the expert created 'Image Finding Descriptor' which can potentially cue the user to look for specific attributes. The system is configured that it can accept DICOM MR studies from any scanner, can be integrated into a PACS diagnostic workstation and requires no additional storage requirements since only transformation matrices (small text files) are stored as DICOM objects with each series of a study. The long-term objective is for the system to automatically process every brain MR study transferred to the PACS so that customized atlases will be available at the time of primary image interpretation. An extension of this module within a PACS environment will include decision support based on case-based reasoning; e.g., display previously interpreted patient studies that are similar to the new patient. The design of the atlas system reported here is based on informatics principles and integrates information from the patient images to customize the atlas and provides context sensitive decision support.

Acknowledgements

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